

On the Conditions determining the Formation of Cloud-spheres and Photospheres. By Arthur W. Clayden, M.A.

In the course of an investigation of the conditions under which clouds may be formed in our own atmosphere certain considerations presented themselves which seem equally applicable to the conditions which determine the position of a stellar photosphere in the mass of a star.

As the spectrum of a star is to a great extent dependent upon the position of the photosphere it seems possible that a survey of these points may help to clear up some of the difficulties attending the interpretation of spectral details.

To begin with it is necessary to ask that it may be taken for granted—

1. That the photosphere of a star is the upper surface of a stratum of clouds.

2. That those clouds are caused by the condensation of some substance from the state of vapour to that of small solid or liquid particles.

3. That the condensation is due to cooling produced by expansion brought about by the ascent of vapour-charged convection currents.

4. That the cooling effect of expansion follows the same general thermodynamic law as is the case in our own atmosphere.

It is true that under the high pressures and temperatures of a star the gradation of temperature may be considerably modified. The transference of heat from one stratum to a higher by conduction and radiation should tend to equalise temperatures, but the increased viscosity due to pressure should tend in the opposite direction. Hence a curve showing the relations of temperature and pressure is not likely to differ very greatly from one plotted in accordance with the expression

$$\frac{\log t - \log t'}{\log p - \log p'} = \frac{\gamma - 1}{\gamma}$$

in which t is the absolute temperature at a pressure p , and t' is the absolute temperature at the reduced pressure p' ; γ is, of course, the ratio of the two specific heats.

In order to argue from the known to the unknown, let us first consider the case of planetary bodies surrounded by an atmosphere consisting wholly of water, a substance whose temperature-pressure relations are well understood.

At temperatures far below freezing-point ice gives off vapour which exerts a certain maximum pressure. As the temperature rises this maximum pressure increases more and more rapidly. This goes on until 365° C. is reached, at which point the maximum pressure is 200.5 atmospheres. If at any temperature the pressure be less than the maximum, evaporation will take place ;

and conversely if the pressure exceed the maximum, condensation will follow until the pressure is reduced to that value.

We can then plot a curve showing the maximum pressures for all temperatures. Let this be done, taking temperatures as abscissæ and pressures as ordinates.

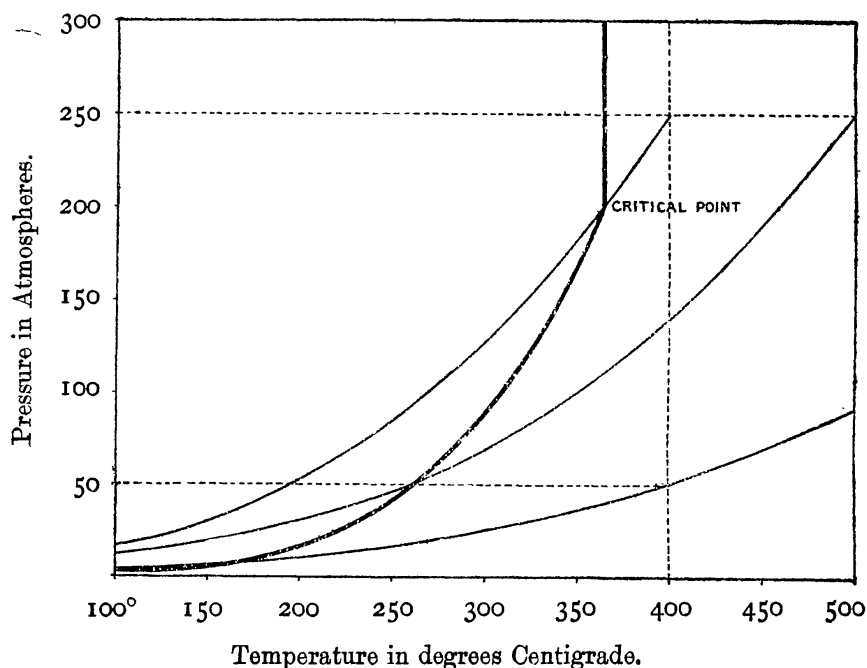


FIG. 1.—Condensation Curve for Water Vapour.

We find the curve rises at first very slowly, and at 100° C. it shows a pressure of one atmosphere. It then turns upwards more and more rapidly until it reaches 365° C. and 200.5 atmospheres. This is the critical point; and if the temperature be higher no increase of pressure can possibly bring about liquefaction. The curve may be regarded as giving the pressures and temperatures of condensation. If, then, the pressure is greater than 200.5 atmospheres, condensation will be effected at the critical temperature. The curve must therefore turn vertically upwards.

Let us now assume that the masses of atmosphere and planet are such that the pressure on the solid surface is 250 atmospheres, and that this surface has a temperature of 400° C. No liquid water can exist on such a surface, but condensation will occur at a certain height.

If the curve of decreasing temperature be plotted, using the expression quoted and giving to γ the proper value for water vapour—namely, 1.3—it will be found that this curve will cut the condensation line very near the critical point, at which temperature and pressure cloud-production will begin.

Suppose, next, that the surface temperature is increased to

500° C. If a similar curve be now plotted it will be found to cut the condensation line at about 50 atmospheres and a temperature of only 260° C. ; that is to say, the effect of increasing the surface temperature of the planet is, not only to drive the cloud-level further up in the atmosphere, but to lower the temperature at which its formation begins.

Again, suppose the surface temperature to be 400° C. but the pressure only 50 atmospheres. The curve then cuts the condensation line at about 160° C. and a pressure of less than 10 atmospheres.

It thus appears that the result of suitably diminishing the mass of a planet may be to produce exactly the same effect upon any cloud-sphere by which it is surrounded as would be brought about by increasing its temperature ; or that a hot planet of large mass might present exactly the same features as a cooler and smaller one.

If we imagine the planetary atmosphere to contain other non-condensable gases this will not affect the conclusions. The changes due to alterations of temperature and pressure will still be in the same direction, and the diagram will serve equally well if we remember that it relates only to the pressures and temperatures of the water vapour present. The actual pressures in the whole atmosphere could be computed by calculating them for the other substances and adding those values.

An inspection of the diagram shows that no cloud-sphere could possibly have a higher base temperature than 365° C. This is one point worth noting.

Next it is evident that if our eyes were so constituted that we could see the radiations emitted from the outer surfaces of such cloud-spheres they would become true photospheres ; and if the distances were great enough we should see these supposed planetary bodies as star-points. If two of them had their cloud-spheres at similar positions in their atmospheres they should present similar spectral features. We should then class them together, although they might really owe their apparent similarity to their true diversity.

Finally it is obvious that a determination of the temperature of the outer surface of the cloud-sphere would be no measure whatever of the temperature of the solid planet beneath.

It is not necessary to point out that these conclusions have an important bearing on the cloud-spheres surrounding the actual planets.

It seems only reasonable to attempt to apply them also to the stars.

Now it is not necessary to make any assumption as to the nature of the substance which makes up the cloud-particles of a stellar photosphere, nor is it necessary to assume that all photospheres are due to the same body. Whatever the substance concerned its condensation-curve would probably present features

similar to those of all bodies for which the requisite data are obtainable.

The argument, however, will be clearer if we start with the assumptions that all photospheres are due to the same substance, and that that is the element carbon. It will be easy later on briefly to consider other possibilities.

We have no measurements of the vapour-pressures of carbon. But there seems some reason to think, from the phenomena of the electric arc, that the vaporisation temperature under one atmosphere pressure is about 3770° absolute. This, then, will correspond to 373° absolute, the boiling-point of water under one atmosphere.

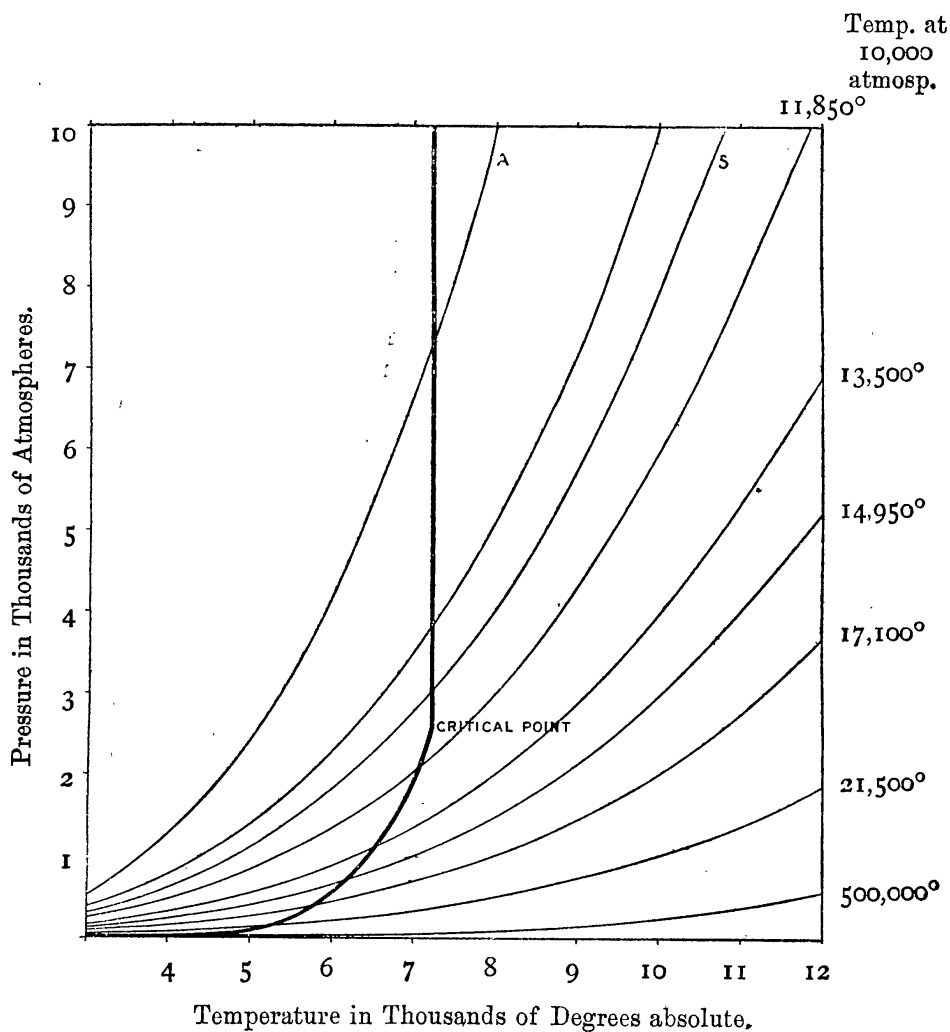


FIG. 2.—Hypothetical Curves for Carbon Vapour.

If we can get some idea as to the critical temperature we can then draw a curve resembling the known curve for water, and feel tolerably sure that our proceedings are reasonable. Messrs.

Wilson and Gray estimated the temperature of the solar photosphere at $6900^{\circ}\text{C}.$; but this is the upper surface of the cloud stratum, which must be cooler than the base. Hence if we take 7200° absolute as the critical temperature we can feel sure that we are at least within the mark, and may be a long way within it.

The difference between 3770 and 7200 is about thirteen times as great as that between 373 and the critical temperature for water. Hence if the condensation-curve for carbon is similar to that for water the critical pressure should be about 2600 atmospheres. If we connect the two points thus fixed by a curve resembling that for water it will serve our purpose, since neither the exact temperatures nor pressures are material to the issue, which rests only on the supposition that the vapour-pressures and temperatures for the photospheric substance can be represented by some curve of the usual type.

Let us draw the curve, and again, for simplicity, consider only the pressures due to the carbon vapour.

Before drawing the curves to represent the changes of temperature and pressure in the stellar mass we are confronted with another unknown—namely, the value to be assigned to γ . According to the determinations of this quantity yet made, it appears that elementary bodies whose molecules are monatomic give a value 1.66; those whose molecules are diatomic give 1.4 to 1.3; while polyatomic molecules give values decreasing with the complexity, but always greater than unity. At stellar temperatures it seems unlikely that there will be polyatomic molecules, so that if we take 1.5 as a working value we shall not be far wrong. Moreover it will soon be evident that a change in the value of γ will in no way affect our general conclusions, but will only modify the numerical examples which serve the purpose of making the argument clearer.

Let us now imagine six stars in which the pressure of 10,000 atmospheres is reached at 8000° , $10,000^{\circ}$, $11,850^{\circ}$, $14,950^{\circ}$, $21,500^{\circ}$, and $500,000^{\circ}$ respectively. Plot the curves of descending temperature and pressure as we pass outwards as before. The results may be tabulated thus:—

Temp. at $p = 10,000.$	Condensation	
	Pressure.	Temperature.
8000	7400	7200
10000	3850	7200
11850	2150	7050
14950	730	6250
21500	130	5250
500000	30?	4400

The table shows that if the initial pressure be far above the critical the result of increasing the initial temperature is to drive the photosphere into regions of diminished pressure. So long as

the pressure of condensation is above the critical, the temperature at which condensation begins remains unaltered ; but as soon as this point is passed, and the curved part of the condensation line is reached, the temperature at which the clouds are formed begins to fall ; that is to say, the effect of raising the internal temperature is to drive the photosphere further *out*, and to *cool it*.

Again, let us imagine that a temperature of $10,000^{\circ}$ is found with pressures of 10000, 8000, 6000, 4000, 2000, and 1200 atmospheres respectively, and tabulate the results as before.

Initial pressure $t = 10,000.$	Condensation	
	Pressure.	Temperature.
10000	3850	7200
8000	3050	7200
6000	2150	7050
4000	1150	6550
2000	420	5850
200	30 ?	4400

The sequence of changes is exactly similar, and the conclusion is that, if the initial temperature is constant, decrease of pressure will produce the same effect as increase of temperature.

Now the pressure at any point is determined by gravity and the mass of the superincumbent gases. It therefore appears that no carbon photosphere can have a higher temperature than the critical, and that the hotter photospheres must be those most deeply seated, or surrounding the most massive stars.

Deep-seated photospheres must mean heavy absorption, high photospheres little absorption.

Inspection of the diagram reveals a number of interesting points, and it is easy to see how the spectra of stars should be modified by altering the ratio of temperature and pressure.] Call this $\frac{T}{P}$.

Let us at the outset give this expression a very high value, so high as to make the curve on the scale of our diagram raised very little above the line of no pressure. Such a star would have no photosphere. If the temperature were suitable small particles of incandescent carbon would be dispersed here and there in a thin mist at a high level. They would be unable to hide the radiation from gases at lower levels or to reverse the light from those among which they were spread. Such stars would be bright-line stars in which the lines would be mixed with a faint continuous spectrum which would begin with a dim radiance in the yellow-green.

As we reduce the ratio $\frac{T}{P}$ the dim radiance will spread and brighten, since condensation under higher pressure means a higher temperature. The mist stratum of the bright-line star

should then pass through denser stages into the condition of a discontinuous stratum of bright photospheric clouds still high up though lower than before. The bright clouds will be overlaid by those gases which lie highest, giving a spectrum showing the dark lines due to absorption. But with a discontinuous stratum of cloud there must be convection. Rising currents will make the clouds, descending currents the interspaces. The light, then, from the descending spaces should be bright lines corresponding with those which are reversed above the clouds.

If we now bear in mind the fact that a star spectrum is an integration of the whole light from the stellar surface, it is easy to see that the bright-line spectrum may be brighter than the continuous; it may be equally bright or it may be less brilliant. If the convection movements were slow the respective results would be bright lines on a continuous background, continuous spectrum alone, or a simple absorption spectrum. It is, however, not likely that all the lines would behave alike, and the result should generally be a white or helium star showing some lines bright and others reversed.

If we may suppose the convection currents sufficiently rapid, then the bright lines due to descending currents should be shifted towards the red, while other bright lines from deeper layers might be undisturbed. We should then have some bright lines fringed on their more refrangible sides by dark companions.

Decreasing the ratio still further the spaces between the cloudlets will close up until we have the complete helium star.

Further progress will yield a yet brighter and hotter photosphere sinking step by step beneath stratum after stratum of gases. As the background gets brighter, helium absorption, having little intensity, becomes less and less obvious. Hydrogen absorption, on the contrary, becomes more and more extensive until it in turn becomes secondary to the absorption due to metallic vapours.

The curves showing the temperature and pressure at which condensation takes place indicate steadily rising pressure, and rising temperature (and, therefore, intrinsic brightness) until the critical point is reached. From this point no further change in $\frac{T}{P}$ can alter the temperature of the photosphere. As it sinks lower and lower the density of absorption increases. If the metallic-line spectrum of the Sun may be supposed to be formed under the conditions represented by the curve S, on passing to the next cooler line we might have the denser absorption of *Arcturus*.

If the ratio $\frac{T}{P}$ be still smaller we come to the curve A. Here the photosphere is still deeper. The outer parts of the super-incumbent gases are much cooler, and compound vapours may be formed. If so, we should expect that the absorption should

consist of metallic lines, flutings, and general absorption of the kind known as smoke-veil ; for instance, *α Orionis* and *Antares*.

Continuing the process, such a spectrum should grow in intensity until the light of the photosphere should be hidden by superincumbent vapours, or even non-luminous clouds formed by condensed metals and compounds. The last glimpse of the incandescent depths should be a dull-red glow.

Such, then, seems to be the normal history of a star.

There is, however, a special case.

Suppose $\frac{T}{P}$ is very high, but that its large value is due to extreme heat, and that P is itself large.

The result should be a very dense gaseous nucleus which should give a continuous spectrum, and therefore act as a deeper-seated photosphere whose light would be veiled by absorption in which that due to carbon vapour would be a conspicuous feature ; but metallic lines would also be present, and if the absorption were great, or the intrinsic brightness of the continuous spectrum small, some of the strong metallic lines would stand out as bright lines—carbon stars. Such stars should pass through the normal sequence as a result of declining temperature, which may explain the former redness of *Sirius*.

It thus appears that bright-line white stars should be associated with nebulae ; that white stars being due to the greatest range of conditions should be most numerous, especially among the smaller stars ; that solar stars should be next in order of frequency, and should form a larger proportion of the massive stars ; that stars with fluted spectra should be comparatively few in number, and should as a rule be massive. Finally carbon stars, demanding exceptionally high pressure and temperature, should therefore be rare and vast.

There are several other deductions which may be drawn.

First, if a binary is formed by the fission of a single star. If the division is equal both stars should be white, or both solar, or beyond. If unequal and differing to a sufficient extent, the smaller would adhere to a Sirian spectrum long after the larger and less cooled had passed into the solar stage or beyond ; as, for instance, *β Cygni*.

Secondly, any determination of the temperature of a photosphere is no guide to the temperature of the star-centre. Neither is the position of the photosphere as shown by the absorption much help. It is possible to have a large hot star showing exactly the same spectrum as a much smaller and cooler one. The ratio $\frac{T}{P}$ may be identical.

So far it has been assumed that carbon is the cause of all photospheres. It is of course possible that different stars may be differently constituted, and that different elements may play similar parts. But all the evidence of the spectroscope indicates a cosmic distribution of the elements best known to us. Moreover

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a moment's thought will show that all that has been said in reference to a carbon photosphere will apply with equal force to any substance whatever. If, then, we can have photospheres formed of some heavier atoms, they should be situated deeper in the mass of the star, and should be overlaid by carbon, which should either form a higher photosphere in turn or should betray its presence by absorption. We ought, then, to have as great a variety of carbon stars as we have of other types. The fact of the rarity of carbon stars is one of the strongest evidences that it is pre-eminently *the* photospheric element. However this may be, the main conclusions here set forth remain unaffected, because they hold good for any substance which forms a photosphere, granting only the four postulates with which we started, and that this substance behaves like all others whose condensation-curves are known.

Observations of Comet a 1903 from Photographs taken with the 30-inch Reflector of the Thompson Equatorial and the Astrographic Equatorial of the Royal Observatory, Greenwich.

(Communicated by the Astronomer Royal.)

Date and G.M.T. 1903.				Apparent R.A.			Apparent Dec.			Corr. for Parl.		log Δ .
d	h	m	s	h	m	s	°	'	"	R.A. s	Dec.	
Jan.	28	5	54	23	7	51	4	30	20	+17	+40	0.2130
Feb.	9	6	6	23	24	31	8	4	53	20	41	0.1945
	9	6	19	23	24	31	8	5	27	21	41	0.1945
	10	6	9	23	26	5	8	24	42	21	41	0.1906
	10	6	24	23	26	6	8	24	59	21	42	0.1906
	11	6	14	23	27	40	8	44	54	21	42	0.1865
	11	6	25	23	27	41	8	45	40	22	42	0.1865
	12	6	22	23	29	18	9	5	27	22	42	0.1823
	17	6	24	23	37	50	10	51	55	24	44	0.1587
	17	6	31	23	37	51	10	52	27	24	44	0.1587
	18	6	22	23	39	38	11	13	58	24	44	0.1534
	23	6	33	23	49	30	13	7	06	27	48	0.1235
	25	6	33	23	52	59	13	52	30	28	49	0.1098
	26	6	34	23	54	59	14	15	49	29	50	0.1024
Mar.	3	6	35	0	5	11	16	0	47	34	57	0.0439
	6	6	44	0	11	14	16	51	31	35	59	0.0334
	11	6	53	0	20	12	17	23	25	44	75	9.9348
	11	7	7	0	20	13	17	23	20	45	76	9.9348
	11	7	25	0	20	14	17	23	17	44	78	9.9348
	12	6	54	0	21	40	17	17	06	46	78	9.9208
	13	6	55	0	23	00	17	4	44	48	81	9.9048
	15	7	4	0	25	8	16	19	43	51	89	9.8730
	16	6	59	0	25	54	15	45	48	+53	+92	9.8570